STUDY ABOUT THE SIMPLE EVALUATION TECHNIQUE OF THE ENVIRONMENTAL VIBRATION WITH WAVE EQUATION

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ABSTRACT :

In environmental vibration evaluation, a simple evaluation technique based on sub-structure-type lumped mass model is proposed. The technique was applied to real site to show the comparative performance with the advanced technique based on 3D-FEM. The response evaluated by simple technique tends to be smaller than that by advanced technique particularly in high frequency, however, this technique is convenient and may be advantageous for in-situ examination for low frequency with a consideration on some safety factors.

KEYWORDS: Soil profile inversion, Environment vibration, Traffic vibration, Sway-Rocking model, Soil-structure interaction

1. INTRODUCTION

Prior to the construction of laboratories or factories which contain delicate instruments such as electron microscopes, vibration assessments may be required to assure that the evaluated vibration level meets the criteria set for specific excitations such as traffics on the nearby road, and so on. In most cases, such assessments have been done by the FEM associated with the Thin Layer Method (TLM) for energy transmission toward infinity. Though this advanced approach is fancy and precise, it is usually a post computation at office after measurements, since it requires relatively long computation time by powerful computers. Sometimes this kind of assessment should be carried out as fast as possible to meet business opportunities, and an in-situ type simple assessment technique has been desired.

In this paper, we will propose a simple technique based on the sub-structure-type lumped mass model with sway and rocking impedances of the foundation subjected to the foundation input motion obtained directly from vibration measurements. These impedances are computed numerically for subsurface models, which may be a simple one inverted from micro-tremor array measurements. The technique was applied at the real construction site and the results are compared with that by the advanced technique to show its adequate performance.

Table 1 Outlines of advanced technique and simple technique

	advanced technique	simple technique
prior information	initial soil profile +	(initial soil profile) +
measurement	microtremor measurement ↓ truck run test	microtremor measurement ↓ truck run test
analysis or calcuration	multilayered soil profile ↓ → equivalent point force	(maltilayer soil profile) ↓ simple soil profile ↓ foundation soil impedance input motion
	↓ ↓	↓ ↓
response analysis	3-D FEM + TLM	Sway-Rocking model

2. SIMPLE EVALUATION TECHNIQUE

2.1. Subsurface Structure Modeling

In simple evaluation technique, the subsurface structure may be assumed by a model with two or three layers, which is determined by inverse analysis to minimize misfits of phase velocity and H/V spectra obtained by array and single point microtremor measurements. The major parameters for each layer are S wave velocity and thickness, alongside with P wave velocity and Poisson's ratio.

2.2. Foundation Input Motion

Foundation input motion is a response of a mass-less rigid foundation under the excitation of propagating waves. Iguchi proposed the approximate method for the foundation input motion by averaging the free field motion as shown in eq. (1) to (3), where A is the area under the assumed foundation (Iguchi, 1982). The coordinates are shown in Fig. 1 with the origin at the centroid of the area.

$$\Delta_x^* = \frac{1}{A}\int_A u_g(x,y)dA \tag{1}$$

$$\Delta_z^* = \frac{1}{A}\int_A w_g(x,y)dA \tag{2}$$

$$\Phi_y^* = -\frac{1}{J_y}\int_A x w_g(x,y)dA \tag{3}$$

$$J_y = \int_A x^2 dA$$

Since the number of sensors for the free field motion is limited in general, we evaluated these integrals by placing sensors at the Gauss's quadrature points for the assumed foundation area and utilize the quadrature.

2.3. Sway-rocking model

Response of the superstructure to the foundation input motion is calculated by a lumped mass system with sway and rocking impedances, subjected to the foundation input motion shown in Fig. 2. The governing equations are shown in eq. (4) and (5), where, M is mass of foundation, J is moment inertia of foundation, $K_{HH}(\omega)$ is horizontal impedance, $K_{HR}(\omega)$ is coupling impedance, $K_{RR}(\omega)$ is rocking impedance, $K_{VV}(\omega)$ is vertical impedance, $U(\omega)$ is horizontal motion at the bottom of the foundation, $\Theta(\omega)$ is rocking motion, $V(\omega)$ is vertical motion, $P_H(\omega)$ is horizontal force, $P_R(\omega)$ is rocking force and $P_V(\omega)$ is vertical force from the superstructure. $\overline{U}(\omega)$ is horizontal foundation input motion, $\overline{\Theta}(\omega)$ is rocking input motion, and $\overline{V}(\omega)$ is vertical input motion. When the foundation is isolated from the superstructure, forces exerted from the superstructure will not be required.

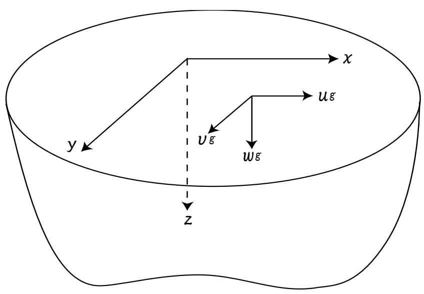


Figure 1 Coordinates for foundation input motion

$$\left(-\omega^2 \begin{bmatrix} M & 0 \\ 0 & J \end{bmatrix} + \begin{bmatrix} K_{HH}(\omega) & K_{HR}(\omega) \\ K_{HR}(\omega) & K_{RR}(\omega) \end{bmatrix} \right) \begin{Bmatrix} U(\omega) \\ \Theta(\omega) \end{Bmatrix} = -\begin{Bmatrix} P_H(U,\Theta) \\ P_R(U,\Theta) \end{Bmatrix} + \omega^2 \begin{bmatrix} M & 0 \\ 0 & J \end{bmatrix} \begin{Bmatrix} \overline{U}(\omega) \\ \overline{\Theta}(\omega) \end{Bmatrix} \tag{4}$$

$$\left(-\omega^2 M + K_{VV}(\omega) \right) V(\omega) = -P_V(V) + \omega^2 M \overline{V}(\omega) \tag{5}$$

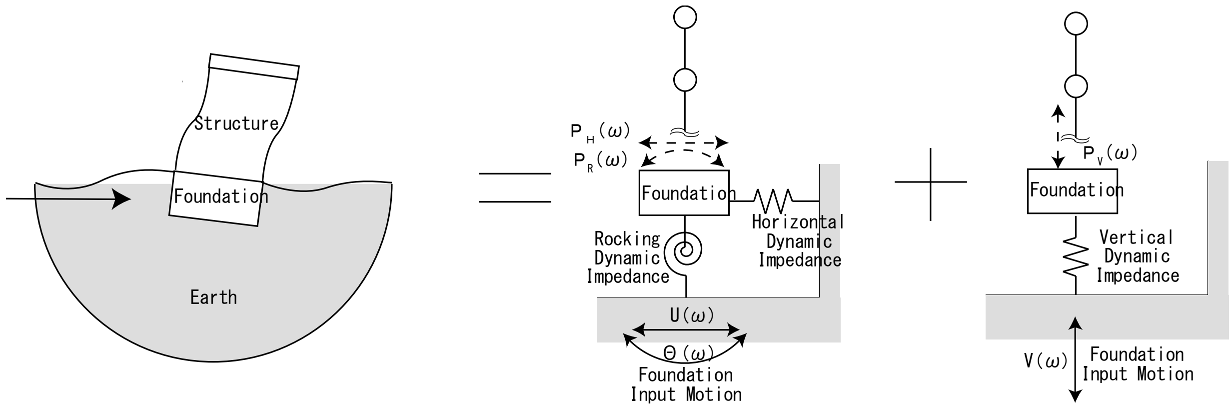


Figure 2 Sway Rocking model

3.APPLICATION AT THE REAL CONSTRUCTION SITE

The simple technique is demonstrated by an application to the real data obtained for the excitations of a running truck loading in a construction site. A 10 ton truck was used for truck excitation and a steel plate on the runway was regarded as an excitation point, which was located 12m away from the center of the assumed foundation area. We had boring data a priori, which suggests the firm layer underlain the 5m of soft soil. The assumed foundation is 3√ 3m square and 1.15m thick.

3.1. Vibration Measurements

Vibration measurements consist of triangular array measurements for micro-tremor, linear array measurements for truck excitations, and simultaneous measurements at four Gauss points in the assumed foundation area for truck excitations. Sensor arrangements are shown in Fig. 3, and the duration for measurements was 15 minutes.

Three component portable seismograph GPL-6A3P's were used for micro-tremor measurements and truck excitations, with sampling time of 1/100 sec, low-pass filtered at 30 Hz. Triangular micro-tremor arrays of three radii, namely 4 m, 8 m, and 16 m, were composed of four seismographs, one at the center and the other three on the circle in a regular triangle shape. Four seismographs at the Gauss points were located at the corner points of 3 m square with the center coincided with the center of the assumed foundation area.

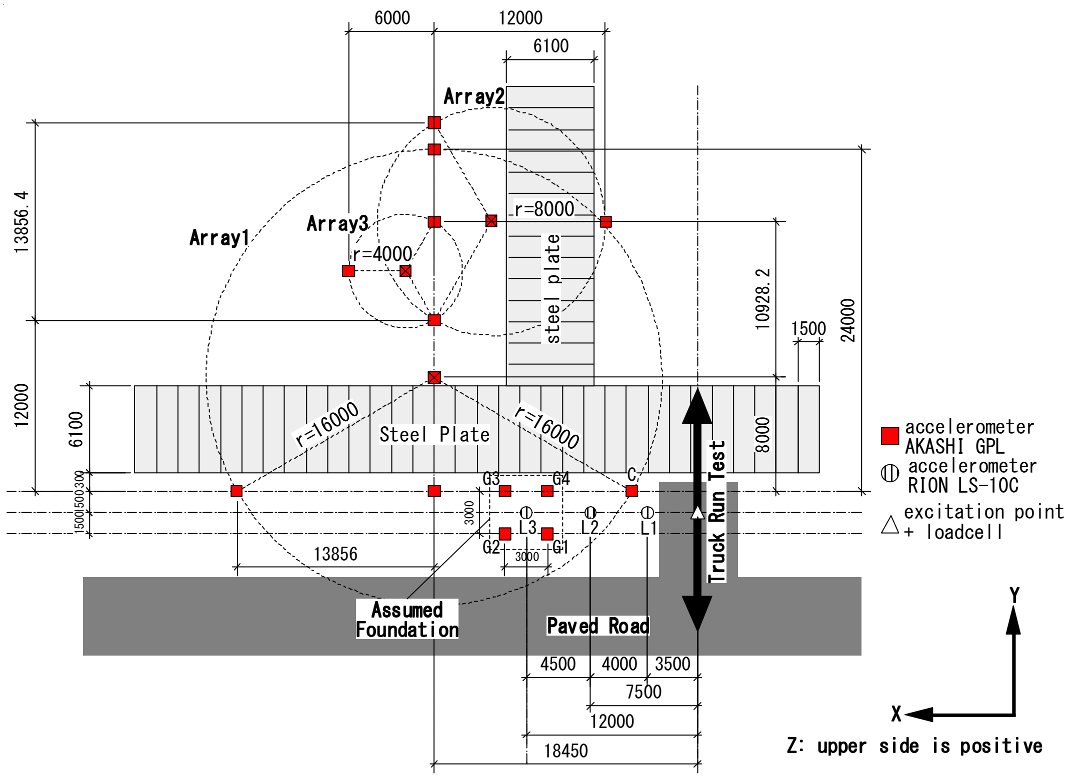
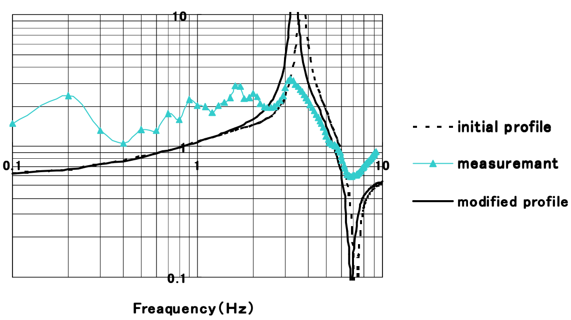


Figure 3 Sensor arrangements and excitation points

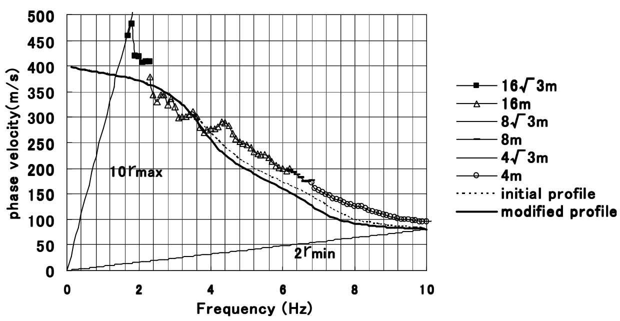
3.2. Subsurface Structure Modeling

H/V spectra were calculated at the point C in Fig. 3 with 4 to 20 samples of 20 seconds data chosen from the stationary parts of the records. A software J-SESAMI was used for the computation of H/V, where Fourier transformed horizontal components in X and Y were averaged for samples and synthesized, then divided by averaged Fourier spectrum of vertical component (Bard, 2004). The dispersion curves for vertical component were obtained with 15 minutes of array data by the SPAC method with a consideration on the effective wavelength for each array radius (Aki, 1957).

H/V spectrum and dispersion curves are shown in Fig. 4 with theoretical counterparts for the fundamental Rayleigh waves, which are computed for the initial soil profile constructed from the boring data and for the modified one by inversion shown in Tab. 1. H/V spectrum exhibits single peak around 2 Hz, and single trough around 7 Hz, both of which are well simulated by the modified profile. The dispersion curves show about 100 m/s at 10 Hz, which may suggest that the surface layer has larger shear velocity than 80 m/s of initial model, and both soil models shows somewhat lower velocities at frequencies larger than 4 Hz.



(a) H/V spectrum



(b) phase velocity dispersion curves

Figure 4 H/V spectrum and phase velocity dispersion curves

Table 2 Initial and modified soil profiles

Layer No.	Initial depth[m]	Modified depth[m]	Vs[m/s]	ρ [kg/m^3]	G[kN/m^2]
1	1.6	1.2	80	1400	9000
2	5.4	5.7	80	1450	9300
3	14.0	11.8	240	1850	106600
4	22.2	19.0	270	1900	138500
5	26.3	23.4	270	1800	131200
6	32.0	29.0	330	1700	185100
7	35.9	33.7	330	1800	196000
8	45.4	45.9	370	1950	267000
9	49.1	50.6	330	1800	196000
layered half space	∞	∞	420	2000	352800

3.3. Simpler Subsurface Structure Modeling and Soil Impedances

Simple subsurface structure model with two or three layers may be advantageous for in-situ simple evaluation. We have tried to construct the simple structures concerning H/V spectrum and dispersion curves in a frequency range of 0.1 Hz and 10 Hz, directly by inversion and trial and error approaches. The Neighbourhood Algorithm was used for inversion with 20 models, reaching to convergence within 25 steps (Maeda, et al. 2005). For the trial and error approach, discretization was made for layer thickness by 1 m and for shear velocity by 5 m/s. The simple subsurface structures thus obtained are shown in Tab. 3.

Table 3 Simple soil profiles

① two-layered model — try-and-error

	Depth[m]	Vs[m/s]	ρ [kg/m^3]	G[kN/m^2]
1st layer	6	80	1400	8960
layered half space	∞	430	2000	369800

② two-layered model — Neighbourhood Algorithm

	Depth[m]	Vs[m/s]	ρ [kg/m^3]	G[kN/m^2]
1st layer	6.0	81.9	1400	9391
layered half space	∞	403	2000	324818

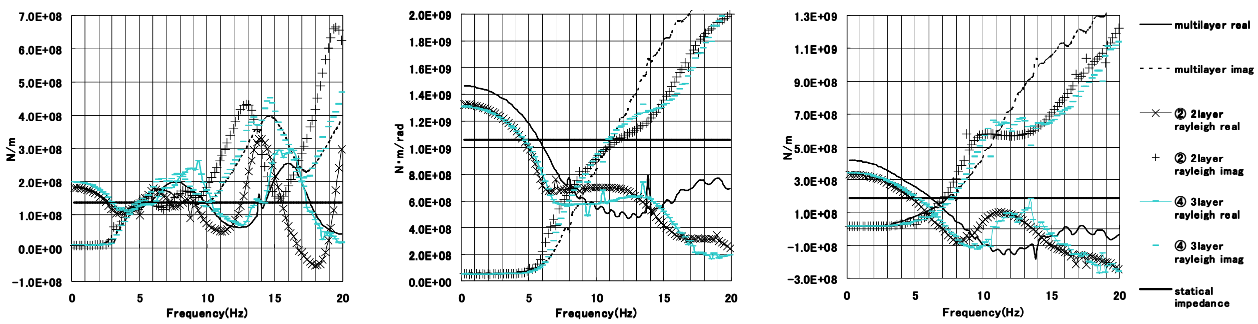
③ three-layered model — try-and-error

	Depth[m]	Vs[m/s]	ρ [kg/m^3]	G[kN/m^2]
1st layer	6	80	1400	8960
2nd layer	56	350	1800	220500
layered half space	∞	420	2000	352800

④ three-layered model — Neighbourhood Algorithm

	Depth[m]	Vs[m/s]	ρ [kg/m^3]	G[kN/m^2]
1st layer	5.8	80.7	1400	9117
2nd layer	47.0	345	1800	214245
layered half space	∞	405	2000	328050

Dynamic soil impedances of the assumed foundation were calculated for modified soil profile and simpler subsurface structures by cylindrical symmetric FEM model. The expanse of the model is 50 m in radial and 52 m in depth with cylindrical solid elements of 0.5 m thick and 0.5 m long in radial direction, with material damping of 1 %. Soil impedances of simpler models are compared with that of modified soil profile in Fig. 5. Horizontal components show relatively good coincidence at lower frequencies, though the fluctuations are large. For rocking and vertical components, simple models exhibit lower value of the real part at low frequencies.

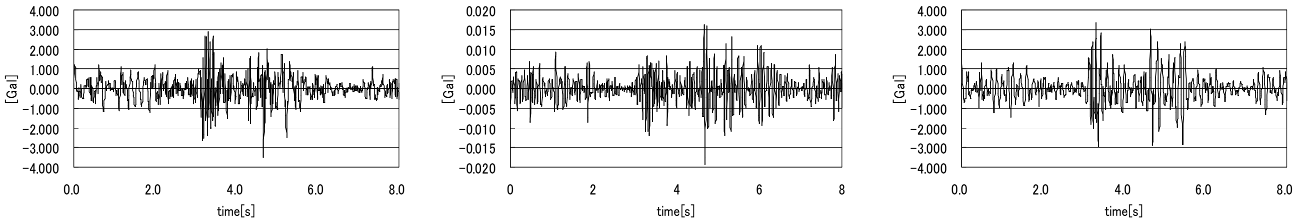


(a)Horizontal component (b)Rocking component (c)Vertical component

Figure 5 Dynamic soil impedances for modified profile and simpler models

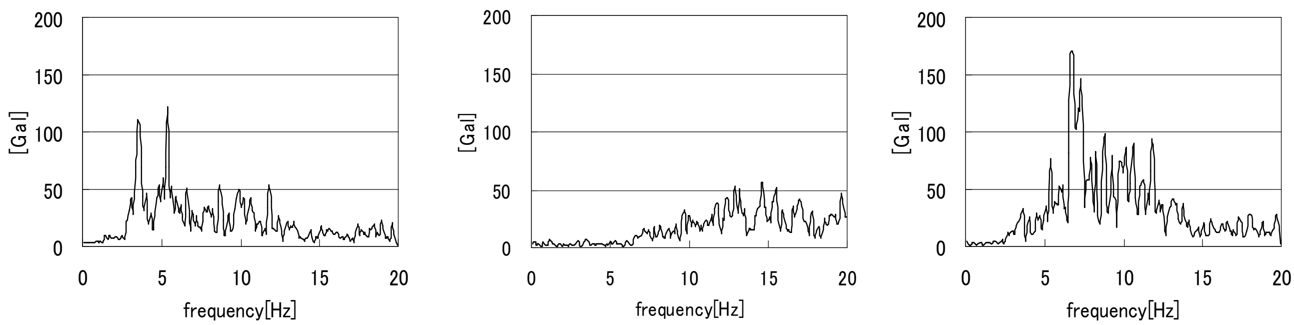
3.4. Foundation Input Motion

Foundation input motion for truck excitation was calculated by eqs. (1) to (3) with 8 seconds data of the records obtained at G1 to G4 shown in Fig. 6 and 7. Rocking component indicates vertical acceleration at the foundation edge. The horizontal component shows two peaks at 4 Hz and 5.5 Hz, while the vertical component shows predominant frequency at 7 Hz.



(a) Horizontal component (b) Rocking component (c) Vertical component

Figure 6 Time history of foundation input motion by averaging free field motion

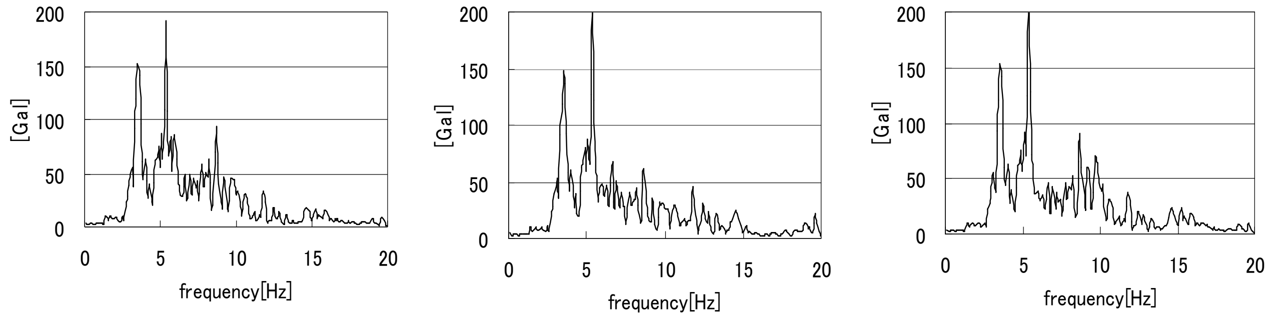


(a) Horizontal component (b)Rocking component (c) Vertical component

Figure 7 Fourier spectra of foundation input motion by averaging free field motion

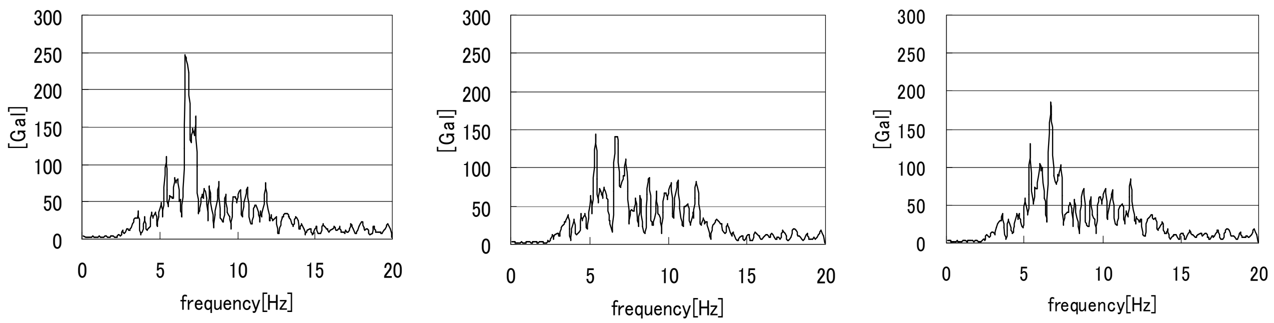
3.5. Foundation Response to Traffics

Foundation response at the top of the foundation for truck excitation was calculated by the sway rocking model with eqs. (4) and (5), where soil impedances shown in Fig. 5 and foundation input motion in Fig. 6 were used. In Fig. 8 and 9, foundation responses are compared for different soil impedances. For horizontal responses, peak frequencies and amplitudes are similar due to the similarity of horizontal impedances at lower frequencies. For vertical responses, the one with modified soil profile shows the largest amplitude, which may stem from lower damping effects represented by its relative larger value of real part at lower frequencies.



(a) Modified soil profile (b) Two-layered model ① (c) Three-layered model ③

Figure 8 Fourier spectrum of horizontal foundation response at the top with different soil springs



(a) Modified soil profile (b) Two-layered model ① (c) Three-layered model ③

Figure 9 Fourier spectrum of vertical foundation response with different soil springs

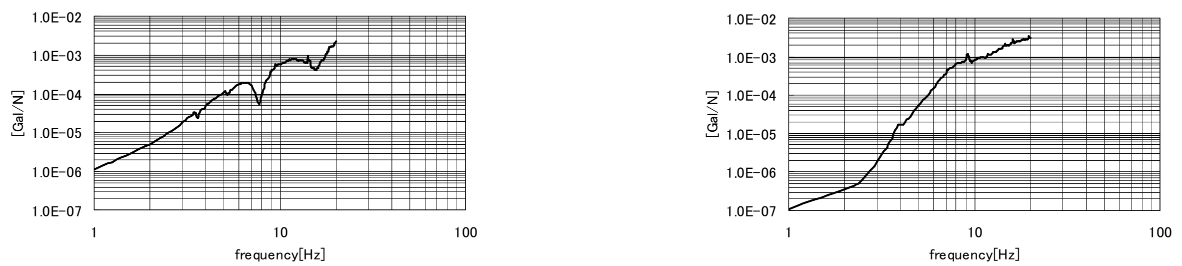
3.6. Comparison of the Simple and the Advanced Techniques

3.6.1. Foundation Response by Advanced Evaluation Technique

Steps for the advanced evaluation technique are summarized as follows.

1) Create FEM model with multilayered soil profile evaluated at the assumed foundation area obtained by inversion on micro-tremor measurements.
2) Evaluate the equivalent vertical point force for the truck excitation by applying the transfer function to the acceleration data obtained at or near the assumed foundation area.
3) Evaluate the foundation response of the FD model with the assumed foundation to the equivalent vertical force.

Computed transfer functions are exemplified in Fig. 10. A tiny peak between 3Hz and 4Hz in horizontal component corresponds to the peak of the H/V spectrum shown in Fig. 4.



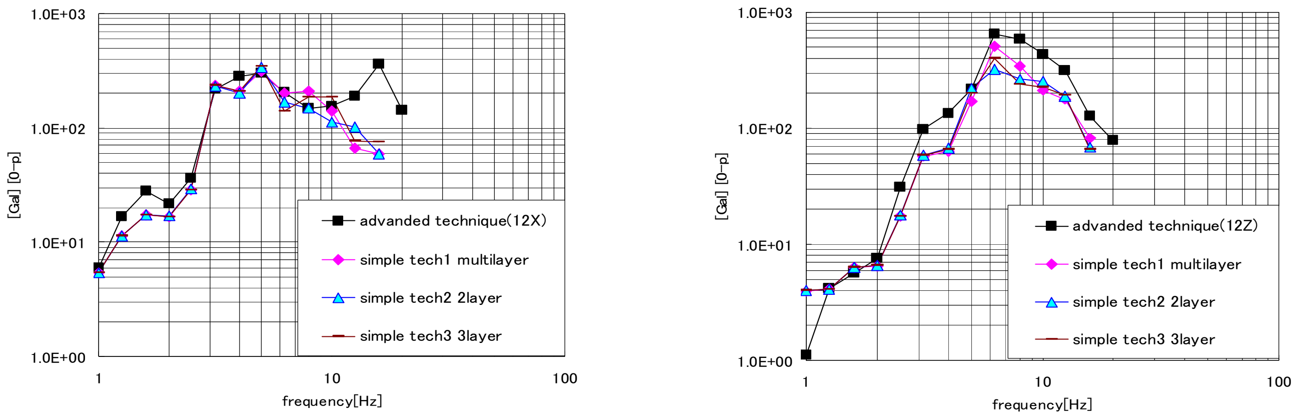
(a)Horizontal component (b)Vertical component

Figure 10 Transfer functions at 12 m

3.6.2. Comparison of the Simple and the Advanced Techniques by octave band analysis

Foundation responses expressed in the 1/3 octave band format are shown in Fig. 11.

For the horizontal component, the simple technique shows a little bit smaller response than the advanced one below 10 Hz and the advanced one exhibits very large amplitude at 15 Hz. For the vertical component, the simple technique shows similar tendency to the advanced one, though the amplitudes are somewhat small. The responses of different soil impedances slightly differ from each other and the simple subsurface model can be justified for this purpose.



(a)Horizontal component (b)Vertical component

Figure 11 1/3 octave band of foundation response

4. CONCLUSIONS

We proposed an in-situ type simple evaluation technique of environmental vibration based on the response of the sub-structure-type lumped mass model with sway and rocking impedances subjected to the foundation input motion obtained directly from vibration measurements. The amplitude of response evaluated by the simple technique tends to be smaller than that by the advanced technique in the high frequency range, which may be attributable to lack of precision in approximate foundation input motion in high frequency; however, this technique is convenient and may be useful for in-situ examination for low frequency with a consideration on some safety factors.

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